Structural Modes Interaction (SMI) Testing

Aeroservoelastic (ASE) Analysis with Flight Test

F-15B Quiet Spike Aeroservoelastic Ground and Flight Test

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Structural Modes Interaction (SMI) Testing and Aeroservoelastic (ASE) Analysis/Test

- Modal Comparison
  - Baseline, QSB-Retracted, QSB-Extended
- Structural Filtering
- Baseline SMI
- Quiet Spike SMI
- ASE Analysis, Model Updating, Flight Test and Results
- Lessons Learned
  - SMI testing for flight readiness – MilSpec vs. practice
- ASE System Identification During Envelope Expansion

Modal Summary

Symmetric Bending Modes Tuned to GVT – Heavyweight

F15-Baseline Freq(Hz)	F15-Baseline Mode Shape	QS-Extended Freq(Hz)	QS-Extended Mode Shape	QS-Retracted Freq(Hz)	QS-Retracted Mode Shape
8.846	**Fuse.1st Bend, Vert Tail 1st, Stab 1st**	**6.693**	**Spike Boom 1st, some Fuse. 1st**	7.001	Fuse.1st
9.492	Left Vert.1st, some Fuse.1st	**9.183**	**Vert.Tail 1st, Spike Boom 1st, Stab.1st, Wing 1st, Fuse.1st**	**8.267**	**Fuse. 1st (mostly Spike Boom), Stab.1st, Vert Tail 1st**
				9.370	Left Vert.Tail 1st, Stab 1st
				9.983	Right Vert.Tail 1st, Stab 1st
10.070	Right Vert.Tail 1st Bend, Fuse.1st(mostly Nose Boom)	10.068	Spike Boom Lat./Vert.1st, Stab.1st, Wing 1st	**10.856**	**Wing 1st, Stab 1st, Spike Boom**
10.913	Wing 1st, Nose Boom and Fore Fuse,	**10.977**	**Wing 1st, Spike Boom 1st, Some Fore Fuse**	**12.979**	**Spike Boom 1st, Stab1st,Wing1st**
14.074	**Stab.1st, Nose Boom, Wing 1st, Vert.Tail 1st**	**14.265**	**Stab.1st, Spike Boom 1st, Wing 1st Bend, Fuse 1st**	**15.343**	**Stab.1st, Spike Boom 1st, Fuse 1st**
16.229	Nose Boom Vert.1st, slight Stab.1st Bend	18.550	Spike Boom 2nd, Stab. 1st		
21.449	**Fuse.2nd, Wing 1st, Nose Boom, Stab. 1st**	**22.470**	**Spike Boom 2nd**	**22.233**	**Spike Boom 2nd**
26.481	Wing 2nd	27.236	Wing 2nd	27.236	Wing 2nd

Structural Filtering

Longitudinal Structural Filter – History

First structural filter

- Notch at 7Hz in anticipation to attenuate Fuse-1st Bending (1970's)
- Sensor location made filter unnecessary (pitch rate sensor located at the antinode)
- Frequency of Fuse-1st Bending modes shifted upwards due to aircraft mods (early 1980's)
- Iron Bird test – stab actuator/backup structure resonance coupled into flight controls near 27Hz third vertical bending mode

Second structural filter

- First-order lag at 6.4Hz added to 7Hz-notch to help eliminate 27Hz oscillation but degraded the longitudinal short period damping - flight test indicated this was unacceptable

Third structural filter

- Notch-lag replaced by two first-order lags (9.4Hz and 10.5Hz)
- Maintained adequate short period phase margin and gain attenuation at 27Hz

Baseline SMI

Objectives

- To define the closed-loop dynamic coupling between the airframe and flight controls
- Determine effects of increasing gains in control system sensor feedbacks up to 8dB (x2.5)

Success Criteria

- Assessment of servoelastic stability margins

Test report: **Structural Mode Interaction Test Results**

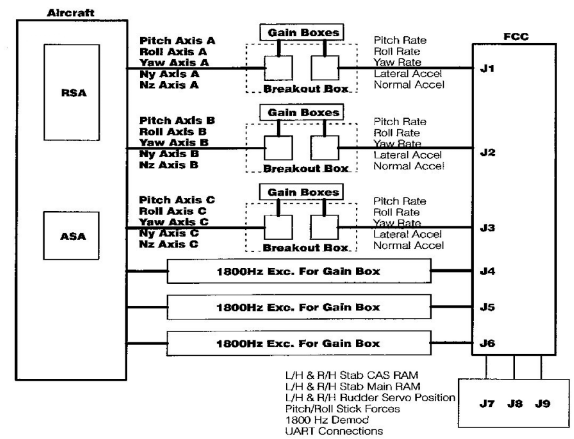
Baseline Aircraft

Test procedure

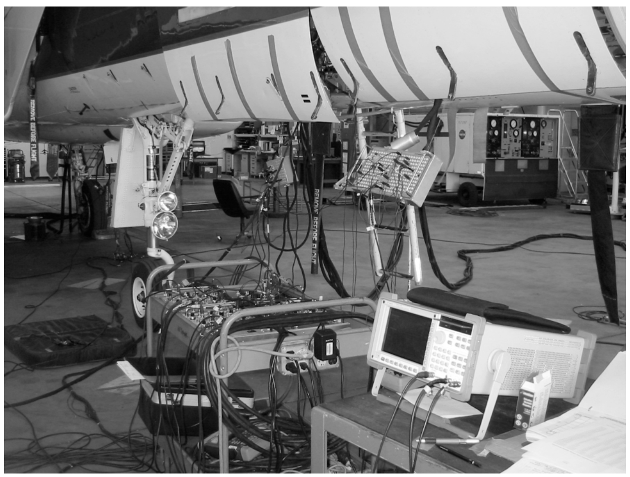
- High-fuel (11,450lbs) , soft tires, CAS α= 16-deg, 7-deg set with probes
- Instrumentation – structural accels, rudder/stab positions, feedback sensors
- Frequency responses – open/closed loops in {Ny, r, p, Nz, q}, 1-40Hz sweeps
- Pilot raps for closed-loop stability margin tests - gain increases in x0.5 increments

Baseline SMI

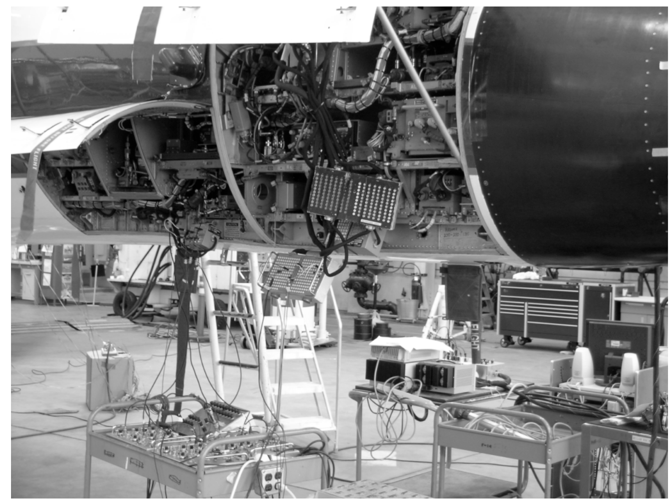
OVERAL TEST SETUP



Baseline SMI



Baseline SMI



Baseline SMI

Baseline SMI

Results

No lateral-directional or gear-down issues - Nz loop mostly open in CAS when gear-down

Limit-cycle oscillations (LCOs)

Nz-gain margin: 3.5dB (x1.5) at α = 16-deg

6dB at α = 7-deg

Summary

Nz feeding back Fuse-1st Bending near 8-9Hz

Pitch rate mostly responds near the Stab-1st Bending near 13Hz

Significant gain increase at both these frequencies in the Nz-loop when closing the Q-loop.
Concern: steep phase crossovers - worst case is when the Nz-loop is excited with all other loops closed (-0.5dB gain peak at 8Hz) compared to when all are open.

Low margins may be a result of excessive nose-boom dynamics coupling with the fuselage, and the feedback accelerometer package located up near the nose

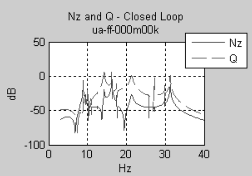
Some frequency differences between model (higher) and test responses

Model results generally conservative

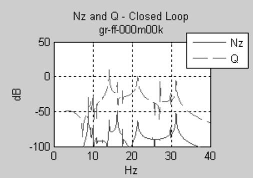
Baseline SMI

Nz loop mostly open in CAS when gear-down

Gear-up



Gear-down

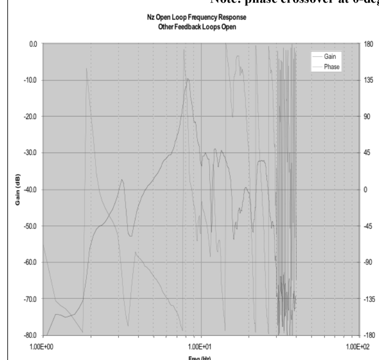


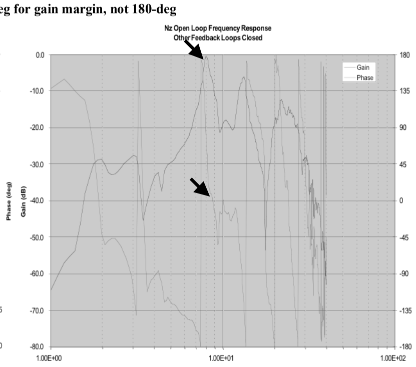
Baseline SMI

Nz-Loop Response (other loops open)

Nz-Loop Response (other loops closed)

Note: phase crossover at 0-deg for gain margin, not 180-deg

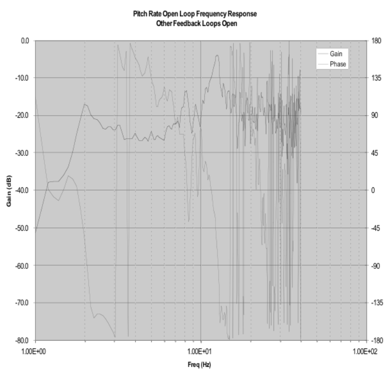


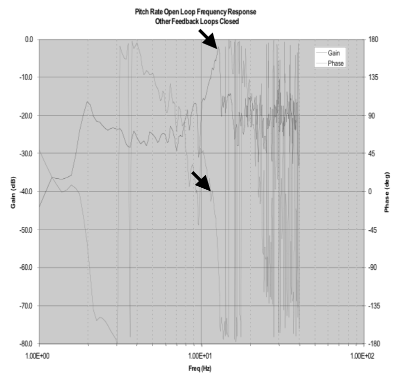


Baseline SMI

Q-Loop Response (other loops open) **Q-Loop Response (other loops closed)**

Note: phase crossover at 0-deg for gain margin, not 180-deg





Baseline/Quiet Spike
SMI-ASE Model Updates

SMI-ASE Model Update Procedure

Compare SMI open loop test responses with SMI model responses

Minimize response difference through optimization on plant {B,C,D} elements

Factors that minimize error used on model matrices to match test data

Use these same factors on appropriate ASE models

- Baseline and Retracted Boom

ASE Model-Updates

Create baseline ASE models

Wavelet-based modal parameter estimation to get (ω, ζ) and update A-matrix

Identify [C, B] of plant $G = C(sI-A)^{-1}B$
MiniMax linear programming with error bounds
MiniMax -> $([C, \Delta C], [B, \Delta B])$ consistent with test data

Flight data

Open-loop identification: KG, GK

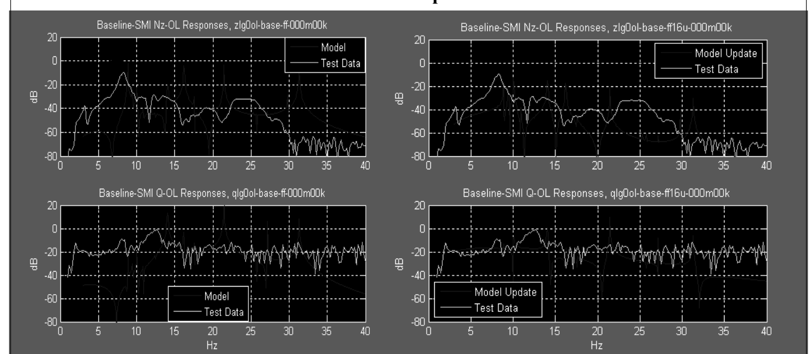
Incorporate updated parameters
calculation of robust stability margins

Baseline SMI

SMI Models vs Test

{Nz,Q} Loop Gains (heavyweight, α = 16-deg, gear up)

Nominal model vs Test data | **Updated model vs Test data**



Quiet Spike SMI

Test procedure (same as Baseline except for boom configurations)

- High (11,450lbs) and low (500lbs) fuel conditions, soft tires, CAS α= 16, 7, and 12-deg
- Extended, retracted, and ½-extended boom states
- Instrumentation – GVT structural accels, rudder/stab positions, feedback sensors
- Frequency responses – open/closed loops in {Ny, r, p, Nz, q}, 1-40Hz sweeps
- Pilot raps for closed-loop stability margin tests - gain increases in x0.1 increments

Quiet Spike SMI

Quiet Spike SMI

Quiet Spike SMI

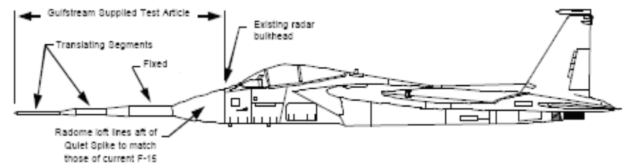
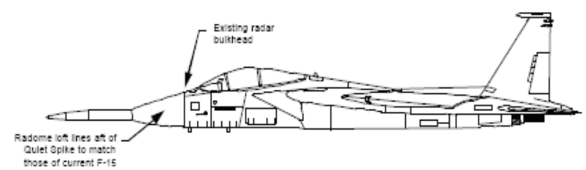


Figure 1: F-15 with Quiet Spike extended.



Quiet Spike SMI

NO lateral-directional anomalies - 8dB satisfied for ALL configurations

Gear-down longitudinal

- at least 8dB margin (spike extended or retracted)

Gear-up longitudinal

- stable-to-LCO (10-13hz) gain factor ranges

- left limit = stable, right limit = LCO

	Retracted	**½-Extended**	**Extended**
Heavy: 16-deg AOA **(Baseline = 3.5dB)**	0-0.8dB LCO at x1.1	3.5-5dB	3.5-6dB (9hz)
Heavy: 7-deg AOA (Baseline = 6dB)	**0.8-1.6dB LCO at x1.2**	5-6dB	6-8dB (9hz)
Light: 16-deg AOA	0dB Unstable	0.8-1.6dB	3.5-6dB
Light: 7-deg AOA	**0-0.8dB LCO at x1.1**	3-3.5dB	6-8dB

Quiet Spike SMI

Results

Nz feedback problematic, BUT no problems when pitch CAS-off

Critical modal frequencies

- Wing-boom-stabilator modes at 10-15hz
- Boom-fuselage (with stab) at 8-10hz
- Steep phase crossovers

Pitch rate loop gains peak between {-3dB,-10dB}@11-12Hz – margins good

Some frequency differences between model (higher) and test responses

Model results generally conservative

Comments

Maintain AOA limit to 12-deg (same results as 7-deg) when gear-up

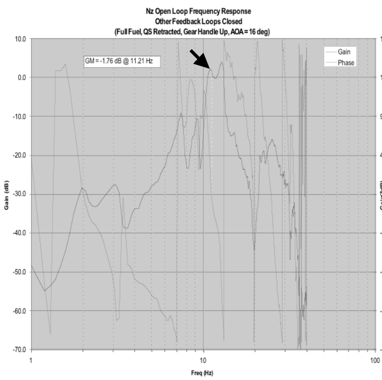
Extended (and ½) mimics baseline aircraft best (3.5-to-6dB for 16-to-7-deg AOA)

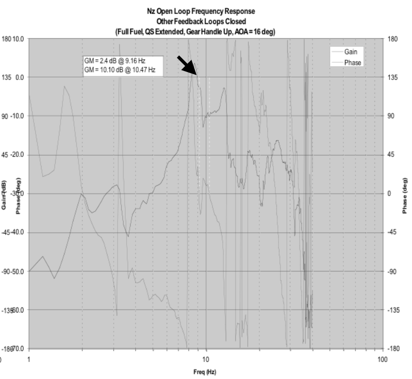
Quiet Spike SMI

SMI Test Data - Loop Frequency Responses (heavyweight, α = 16-deg)

Nz Loop Response (other loops closed , retracted boom) **Nz Loop Response (other loops closed , extended boom)**

Note: phase crossover at 0-deg for gain margin, not 180-deg



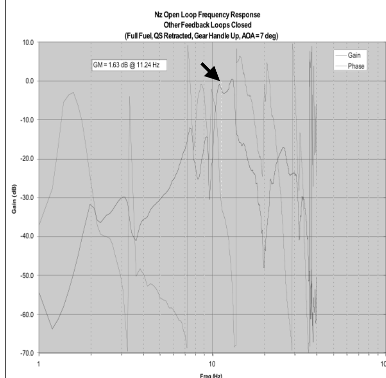


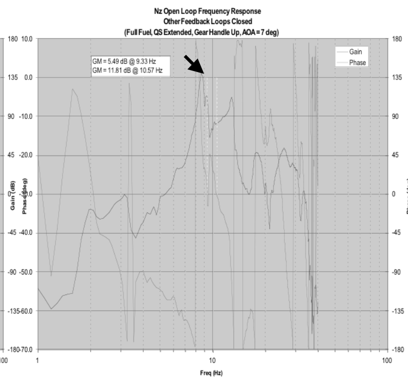
Quiet Spike SMI

SMI Test Data - Loop Frequency Responses (heavyweight, α = 7-deg)

Nz Loop Response (other loops closed , retracted boom) **Nz Loop Response (other loops closed , extended boom)**

Note: phase crossover at 0-deg for gain margin, not 180-deg



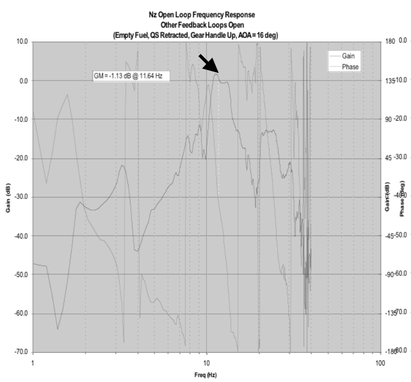


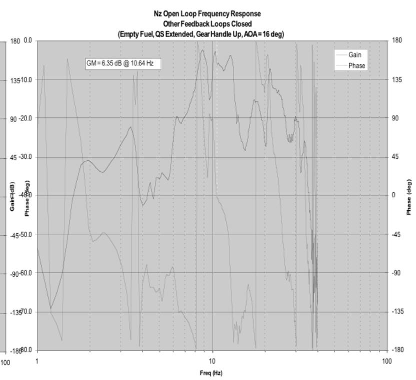
Quiet Spike SMI

SMI Test Data - Loop Frequency Responses (lightweight, α = 16-deg)

Nz Loop Response (other loops *open*, retracted boom) **Nz Loop Response (other loops closed , extended boom)**

Note: phase crossover at 0-deg for gain margin, not 180-deg



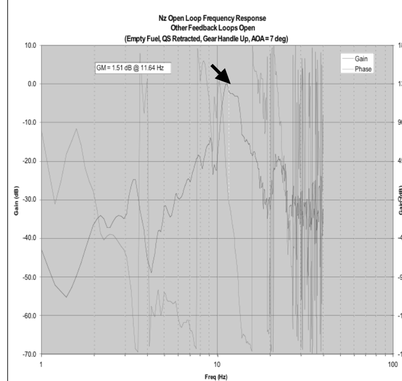


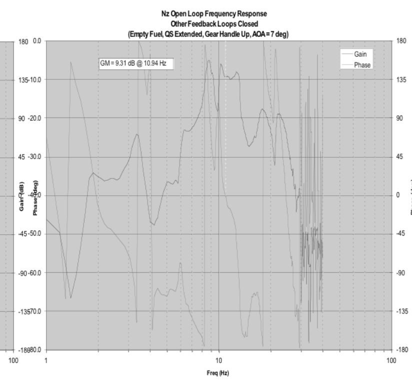
Quiet Spike SMI

SMI Test Data - Loop Frequency Responses (lightweight, α = 7-deg)

Nz Loop Response (other loops *open*, retracted boom) **Nz Loop Response (other loops closed , extended boom)**

Note: phase crossover at 0-deg for gain margin, not 180-deg

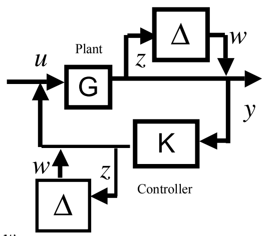




ASE Analysis

Closed-Loop Complementary Sensitivity μ-Analysis

Multi-loop robust stability analysis for multivariable gain plots
- applies to **modal stabilization criteria**



Uses norm-based multivariable closed-loop transfer functions

μ[KG (I-KG)] **(input uncertainty)**
μ[(I-GK)GK] **(output uncertainty)**

For output uncertainty perturbation

$w = \Delta z$, $\|\Delta\| < 1$

$y = (I + \Delta)G\, u$, $z = GK(w + z) = (I - GK)^{-1}GK\, w$

indicates closed-loop stability guaranteed if

$\|(I - GK)^{-1}GK\Delta\| < 1$ (0dB), (log $\|T\Delta\| <$ log $\|T\|$ since $\|\Delta\| < 1$)

For input uncertainty perturbation

$w = \Delta z$, $\|\Delta\| < 1$

$u = (I + \Delta)K\, y$, $z = KG(w + z) = KG(I - KG)^{-1}\, w$

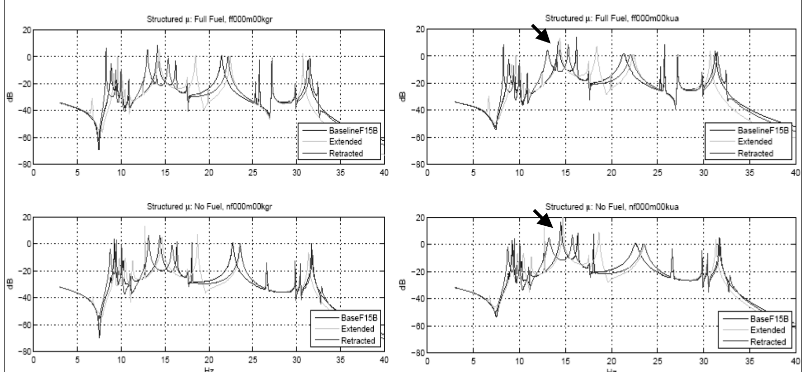
indicates closed-loop stability guaranteed if $\|KG(I - KG)^{-1}\Delta\| < 1$ (0dB)

ASE Analysis

SMI Models – Closed-Loop μ-Analysis (Top – heavyweight, Bottom – lightweight)

Gear-down, Mach=0, H=0k, α = 0-deg **Gear-up, Mach=0, H=0k, α = 0-deg**

[model shows some conservatism in responses relative to test data]



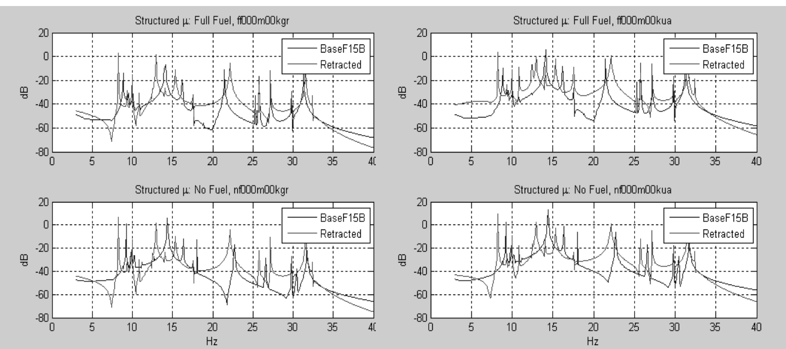
ASE Analysis

Updated SMI Models – Closed Loop μ-Analysis

(Top – heavyweight, Bottom – lightweight)

Gear-down, Mach=0, H=0k, α = 0-deg **Gear-up, Mach=0, H=0k, α = 0-deg**

[comparable peaks near {8, 13, 22}-Hz, no-fuel and gear-up slightly worse]



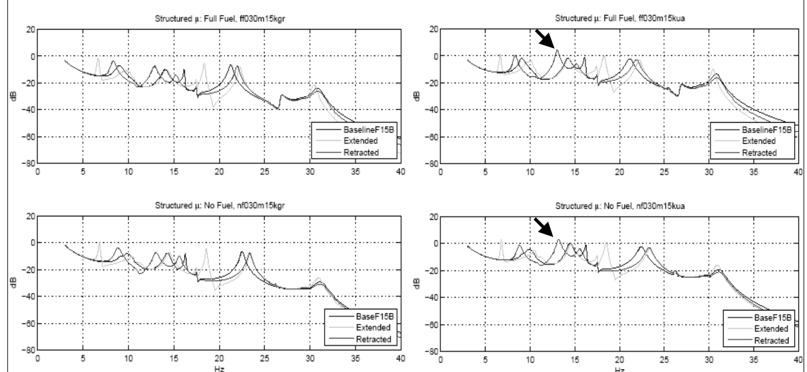
ASE Analysis

ASE Models – Closed-Loop μ-Analysis

(Top – heavyweight, Bottom – lightweight)

Gear-down, Mach=0.3, H=15k, α = trim (12-deg) **Gear-up, Mach=0.3, H=15k, qbar = 75psf**

[gear-up makes all responses worse]



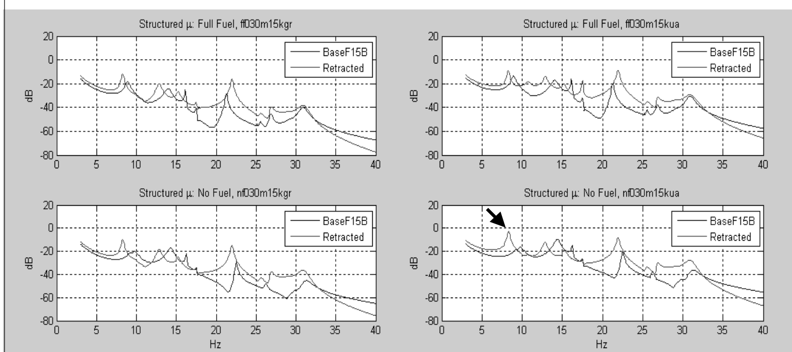
ASE Analysis

Updated ASE Models – Closed-Loop μ-Analysis

(**Top – heavyweight, Bottom – lightweight**)

Gear-down, Mach=0.3, H=15k, α = trim (12-deg) **Gear-up, Mach=0.3, H=15k, qbar = 75psf**

[gear-up slightly worse, retracted difference near 8Hz – not so bad at 13Hz]



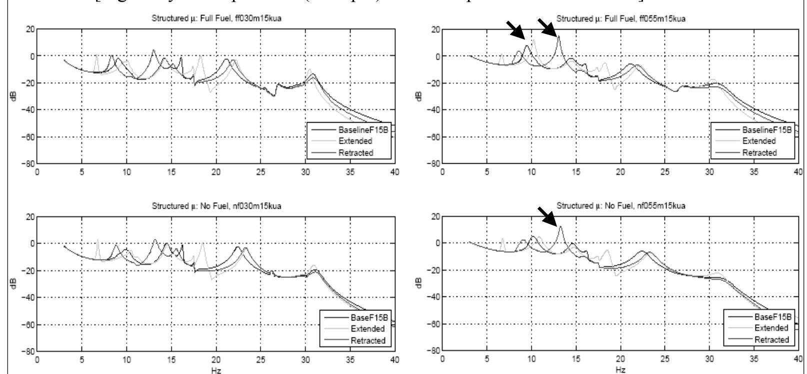
ASE Analysis

ASE Models – Closed-Loop μ-Analysis

(**Top – heavyweight, Bottom – lightweight**)

Gear-up, Mach=0.3, H=15k, qbar = 75psf **Gear-up, Mach=0.55, H=15k, qbar = 253psf**

[higher dynamic pressure (+178psf) makes responses worse < 15Hz]



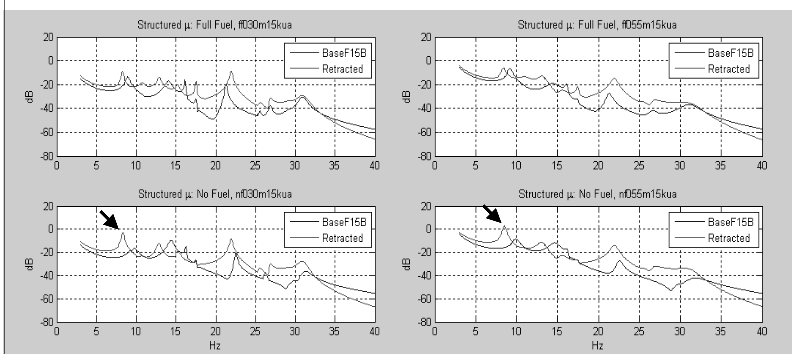
ASE Analysis

Updated ASE Models – Closed-Loop μ-Analysis

(Top – heavyweight, Bottom – lightweight)

Gear-up, Mach=0.3, H=15k, qbar = 75psf **Gear-up, Mach=0.55, H=15k, qbar = 253psf**

[higher dynamic pressure slightly worse, concern near 8Hz lightweight]



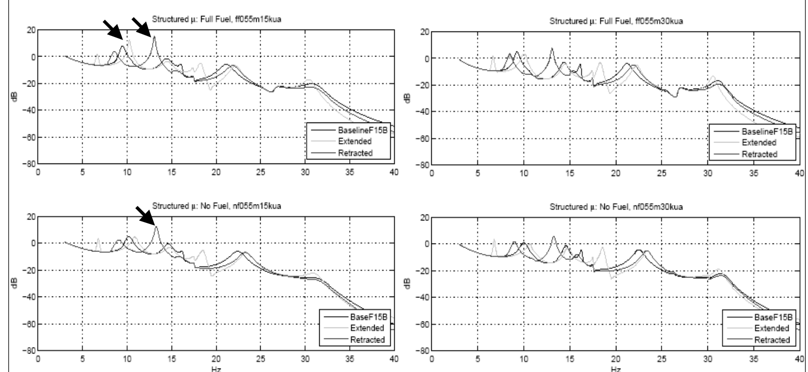
ASE Analysis

ASE Models – Closed-Loop μ-Analysis

(Top – heavyweight, Bottom – lightweight)

Gear-up, Mach=0.55, H=15k, qbar = 253psf **Gear-up, Mach=0.55, H=30k, qbar = 133psf**

[higher dynamic pressure (+120psf) makes responses worse < 15hz]



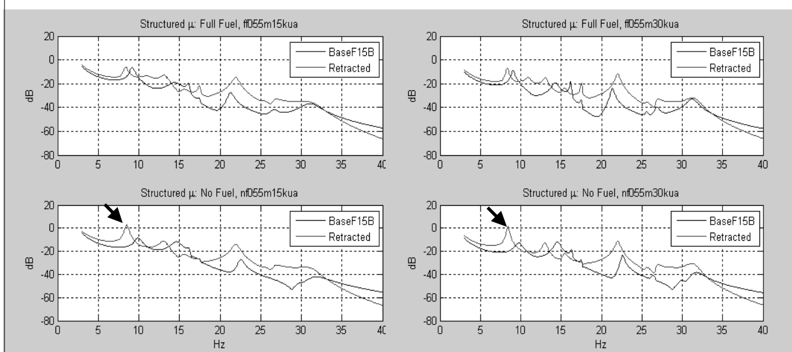
ASE Analysis

Updated ASE Models – Closed-Loop μ-Analysis

(Top – heavyweight, Bottom – lightweight)

Gear-up, Mach=0.55, H=15k, qbar = 253psf **Gear-up, Mach=0.55, H=30k, qbar = 133psf**

[no major dynamic pressure effect, retracted lightweight concern]



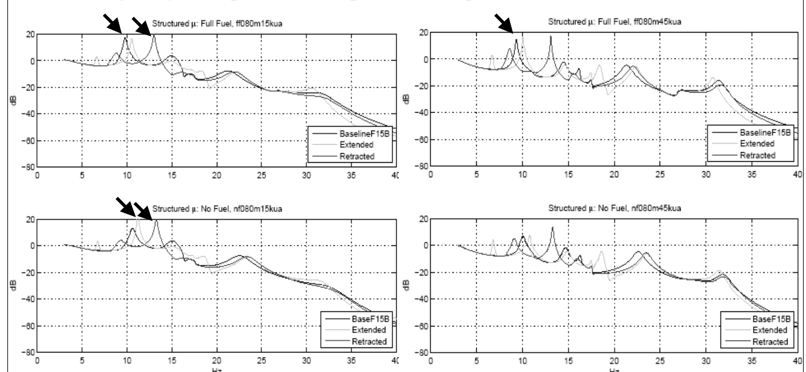
ASE Analysis

ASE Models – Closed-Loop μ-Analysis

(Top – heavyweight, Bottom – lightweight)

Gear-up, Mach=0.8, H=15k, qbar = 535psf **Gear-up, Mach=0.8, H=45k, qbar = 138psf**

[higher dynamic pressure (+400psf) makes responses worse < 15Hz]



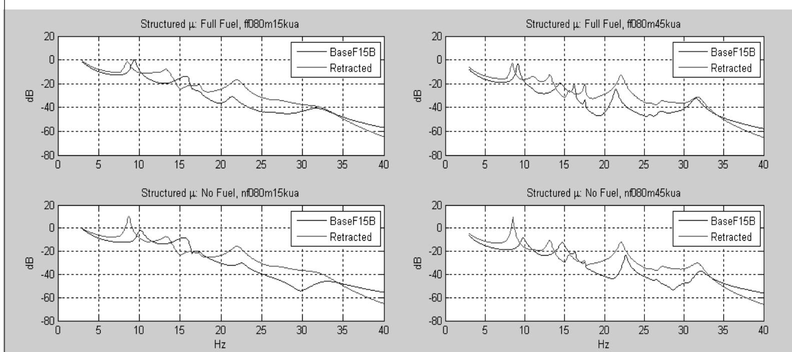
ASE Analysis

Updated ASE Models – Closed-Loop μ-Analysis

(Top – heavyweight, Bottom – lightweight)

Gear-up, Mach=0.8, H=15k, qbar = 535psf **Gear-up, Mach=0.8, H=45k, qbar = 138psf**

[higher dynamic pressure (+400psf) is not noticeably worse, concern retracted light]



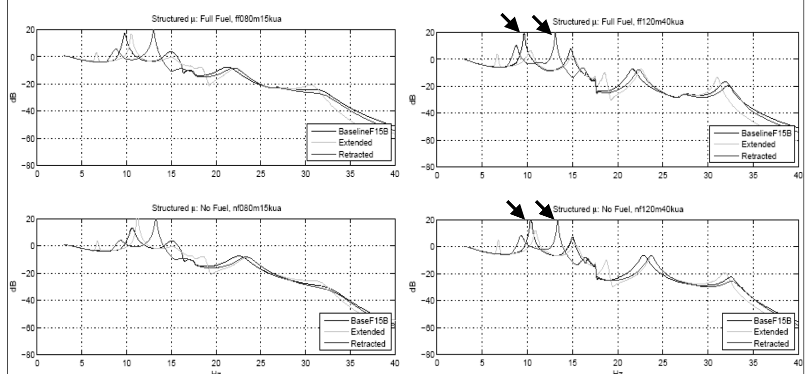
ASE Analysis

ASE Models – Closed-Loop μ-Analysis

(Top – heavyweight, Bottom – lightweight)

Gear-up, Mach=0.8, H=15k, qbar = 535psf **Gear-up, Mach=1.2, H=40k, qbar = 395psf**

[supersonic at lower dynamic (-140psf) pressure not necessarily better]



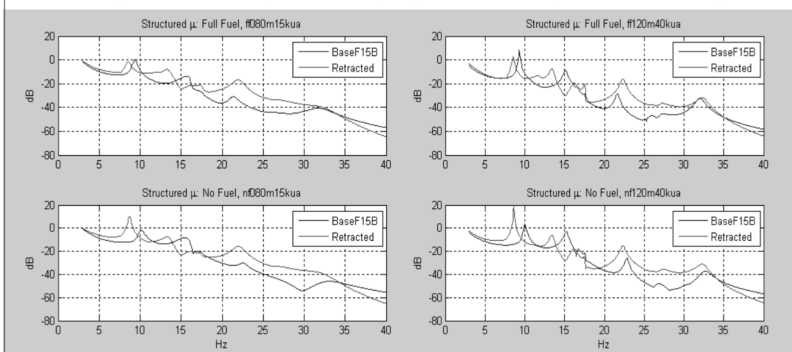
ASE Analysis

Updated ASE Models – Closed-Loop μ-Analysis

(Top – heavyweight, Bottom – lightweight)

Gear-up, Mach=0.8, H=15k, qbar = 535psf **Gear-up, Mach=1.2, H=40k, qbar = 395psf**

[supersonic at lower dynamic (-140psf) pressure noticeably worse, retracted light]



ASE Analysis

Conclusions

Model responses generally conservative

ASE trends correlate with SMI test results

- Extended boom more like baseline
- Retracted generally worse than extended boom
- No problems in pitch CAS-off configuration

Retracted boom-fuse-stab (9Hz) and boom-stab-wing (13Hz) biggest concerns

- Lesser concern with extended boom near 9Hz

All responses should be judged relative to baseline 3.5dB margin at 9Hz

- Roll-off structural filtering helps for higher frequencies (> 9Hz)

ASE Flight Clearance

Hazard

- LCO in CAS mode

LCO

- Mild-to-extreme LCOs not catastrophic from SMI tests: <1-deg stab
- Low damping from raps and gradual LCO onset expected as warnings
- Expect mild LCO onset with dynamic pressure
- Expect time-to-react will be more than adequate
- Simulation tests show no controllability issues with LCO perturbations

Mitigations

- Avoid turbulence
- Turn pitch CAS-off
- Pilot as sensor complements control room

ASE Flight Clearance

LCO: Retracted, Lightweight, AOA = 16-deg, pitch rap, nominal gain = x1.0

[redacted]

ASE Flight Clearance

Control Room

- Motion Pack angular rates and accels (400sps)
- Stabilator/rudder/aileron positions (400sps)
- Spike boom tip accels (400sps)
- Stick/pedal positions

Establish ASE stability boundaries

- Power approach (gear-down) retracted and extended
- Gear-up extended - work up in altitude and dynamic pressure
  - Repeat with gear-up retracted

Spike-Retracted ASE Test Points

Spike-Extended Maneuvers Summary (CAS-on)

- Boom modes match predictions
  - First lateral, 6.5-7Hz
  - Fuselage-boom-stab, 9-10Hz
  - Damping = 0.02+ adequate
- ASE – no noticeable structural response in surfaces/feedbacks
- Extended boom configuration matches baseline F15B

Proposed ASE spike-retracted, gear-up, CAS-on clearance

- Mach, dynamic pressure, and control system parameters

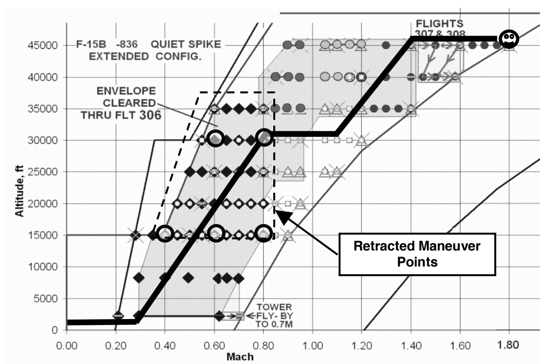
Objective

- **Determine ASE margins relative to SMI test and analysis**

Spike-Retracted ASE Clearance

Accelerate with raps, CAS-on - If LCO, abort that altitude (CAS-off)

0.4M-to-0.6M @ 15 kft
0.6M-to-0.8M @ 30 kft
0.6M-to-0.8M @ 15 kft



Spike-Retracted ASE Test Points

Spike-retracted, CAS-on maneuvers summary

Cleared nearly all the subsonic envelope to 0.8M

- 15k, 30k, 25k, 8k, and tower-flyby with landing

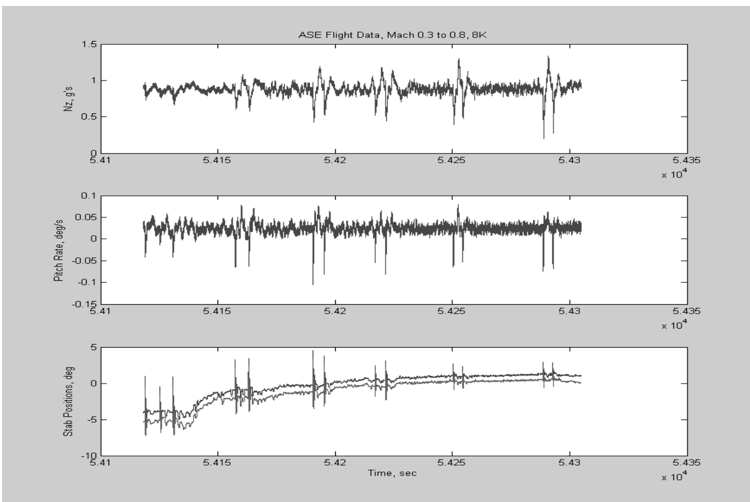
Proposed to clear supersonic envelope for transitions

Pitch raps, CAS-on, 0.8M in 0.05M increments to supersonic condition at altitude

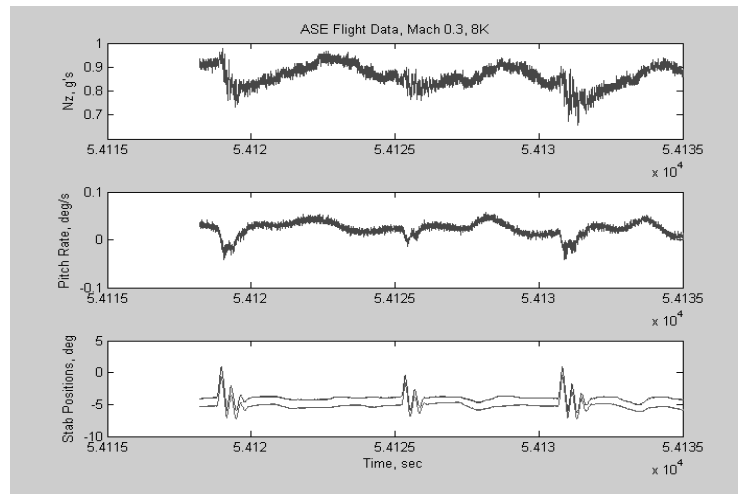
Abort call: slow down to subsonic, pilot option for CAS-off

Mitigations: no subsonic ASE concerns, CAS-off sim results

Spike-Retracted ASE Data at 8K



Spike-Retracted Mach 0.3 Test



Quiet Spike: SMI / ASE

- Structural Mode Interactions (SMI) / Aeroservoelasticity (ASE)
  - Ground SMI test results unsatisfactory: raised some concern about aeroservoelastic (ASE) stability margins in flight
  - ASE analysis couples aerostructural with control dynamics
  - Extensive ASE flight clearance was devised based on the SMI margins, with ASE models updated from SMI results
- Flight test results
  - Extended-boom configuration much like baseline F15B
  - Retracted-boom: worse-case at lowest dynamic pressure
  - No ASE problems in flight despite poor SMI margins and ASE predictions (gear-up, longitudinal, CAS-on, retracted-boom)

Lessons Learned

Structural Dynamics / Aeroservoelasticity

- Higher dynamic pressure test points exhibit less ASE response in the stabilators even with greater Nz-feedback response.
- Attributed to higher damping on the stabilators than the analysis indicated.
- Conservative factors in the analysis include using zero structural damping and a crude model-updating procedure based on limited SMI data.
- Results demonstrate that the SMI test, although used as a strong indication of possible stability issues in flight, is not definitive as flight test predictor.
- Updated analysis showed a possible ASE problem in flight, but purely gain-based robust stability analysis for the multi-loop feedback configuration, which is also somewhat conservative (arbitrary phase variations assumed).
- Linear and nonlinear system identification procedures are being investigated for deeper insight/understanding of the ASE dynamics.
- No two aeroservoelastic analyses are the same! (X29, AAW, etc.)

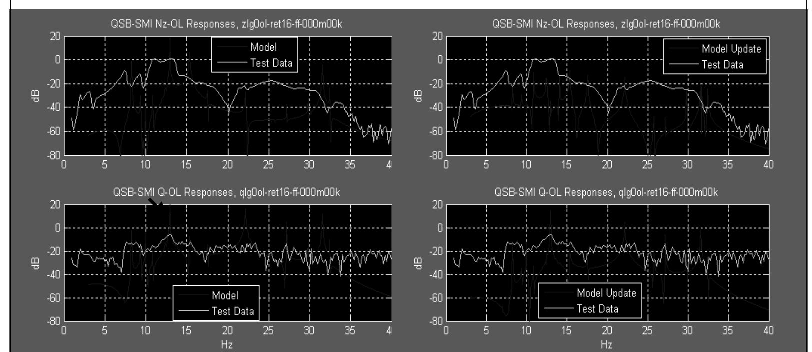
Quiet Spike Video

Quiet Spike SMI

SMI Models vs Test

{Nz,Q} Loop Gains (heavyweight, 16-deg, retracted boom, gear up)

Nominal model vs Test data **Updated model vs Test data**

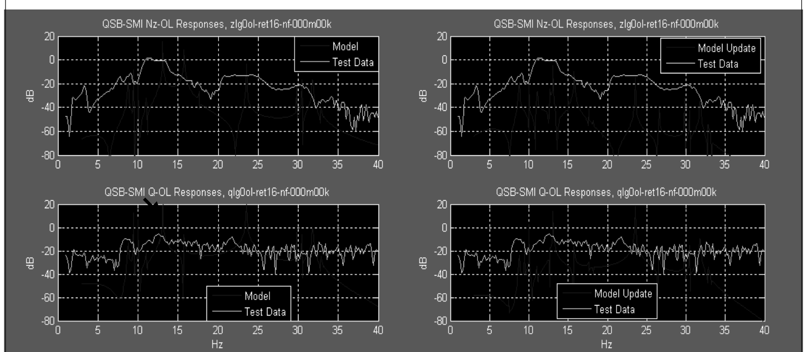


Quiet Spike SMI

SMI Models vs Test

{Nz,Q} Loop Gains (lightweight, 16-deg, retracted boom, gear up)

Nominal model vs Test data | **Updated model vs Test data**



Quiet Spike SMI

SMI Models vs Test

{Nz,Q} Loop Gains (lightweight, 7-deg, retracted boom, gear up)

Nominal model vs Test data | **Updated model vs Test data**